

Observation of an Intense Deep-Water Intrusion in Puget Sound

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Introduction

Bottom water intrusions are one of the major circulation features of Puget Sound (Cannon et al., 1990) and are a major source of sub-tidal variability (Bretschneider et al., 1985). Together with tidal pumping at the Narrows, intrusions are responsible for the short residence time of water within the main basin and are crucial to removal of contaminants. Deep-water intrusions are formed during neap tides when the mixing over the Admiralty Inlet sill is at a minimum. The water formed during neap tides replaces the resident deep water within the main basin. When tidal mixing over the sills is more intense, intermediate water intrusions may occur with the formation of an advectively forced, step-like density structure within the main basin.

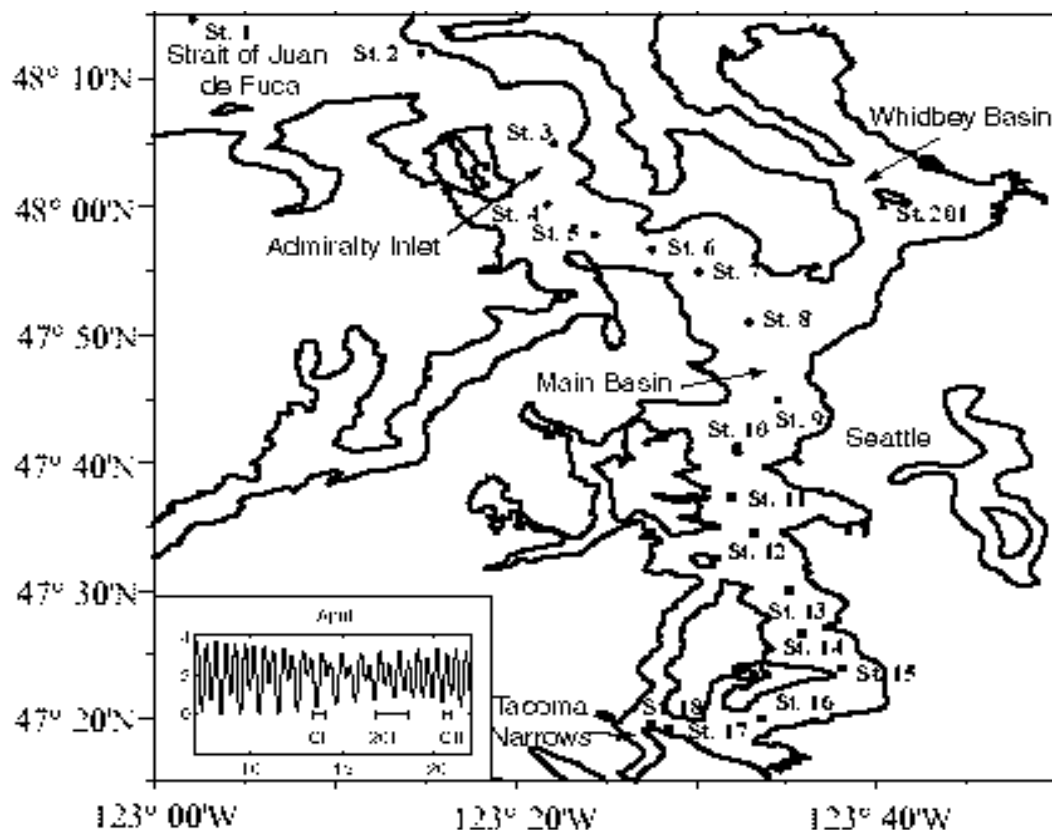


Figure 1. Map of Puget Sound with location of stations and Seattle tides during the study. Stations 1 to 10 were occupied during the intrusions on 13–14 April 1997 (section C-1); stations 10 to 18 were occupied one week after the intrusion on 20 April 1997 (C-11). Station 201 was occupied on 17 April 1997.

The dynamics of chlorophyll *a* (chl *a*) at depth in Puget Sound have been linked to bottom water intrusions by Winter et al. (1975), who observed increased pigment concentrations associated with increased salinity. They argued that sinking could not account for their observations. During our cruises in April 1997 we observed the transport of waters with high chl *a* concentration to depth and the disappearance of pigments within these waters.

Here we present observations from two hydrographic sections in April, 1997; the first section took place during an intense neap tide intrusion over the Admiralty Inlet sill region and the second section was performed a week later within the main basin.

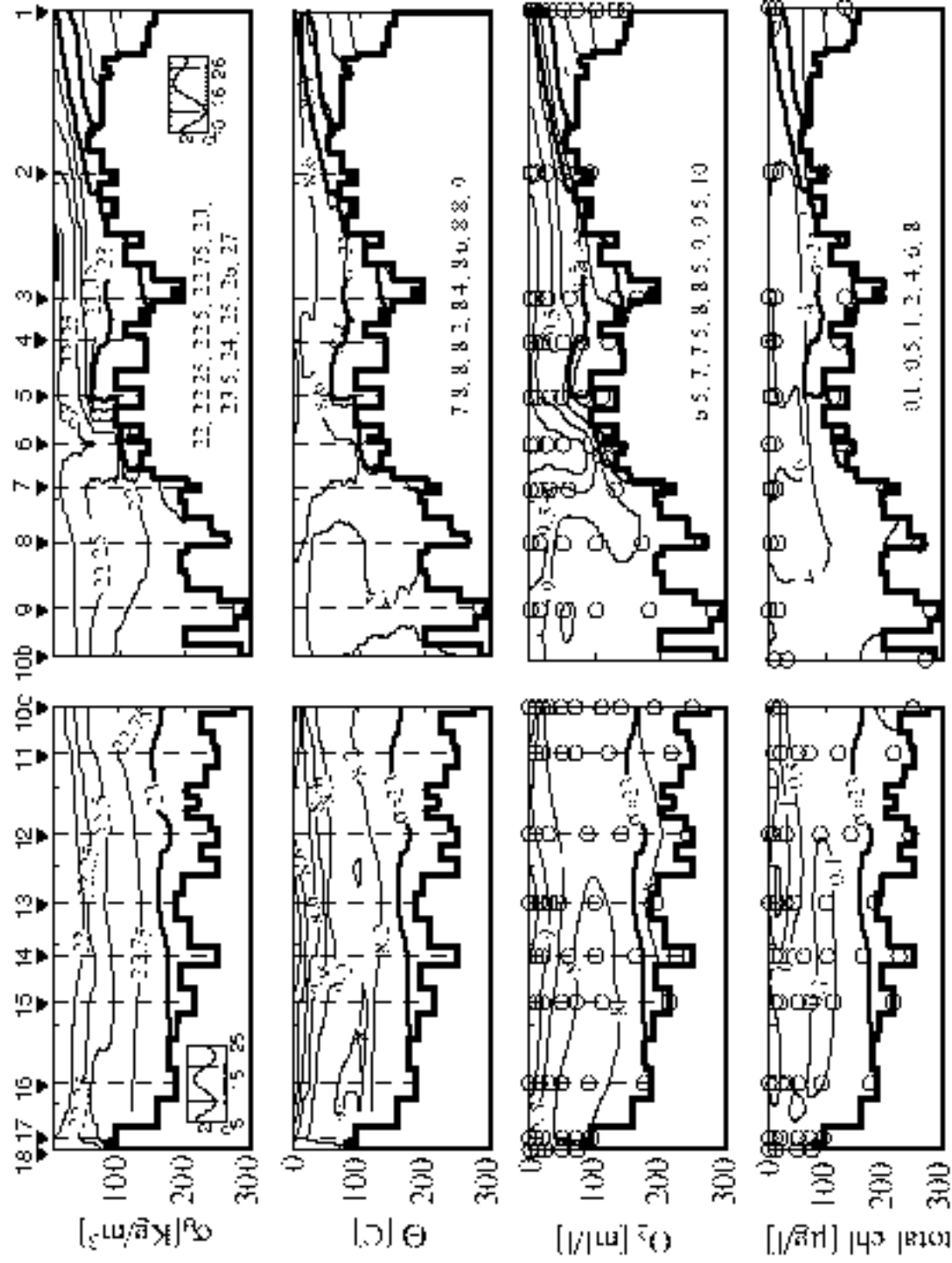
Methods

Hydrographic data were collected during two survey sections conducted *aboard R/V Clifford A. Barnes* on 13–14 (C-I) and 20 (C-II) April 1997. Hydrographic casts were performed at 18 stations (Figure 1); additional casts were taken at Station (St.) 10, i.e., at the beginning and end of each of the two sections. The first cruise was planned to coincide with the neap tide intrusion at Admiralty Inlet (Figure 1), while the second one was intended to determine how far the deep-water intrusion propagated through the main basin during a one-week period. Additional hydrographic measurements were taken in between our two sections during a University of Washington student cruise to Whidbey Basin (St. 201, Figure 1).

The sampling design (Figure 1) followed the deepest route through the main basin and included the deep holes in the bathymetry where the densest water was expected to be found. The hydrographic sections were performed from north to south and occurred mostly during flood tides (Figure 1). Station 10a was visited before section C-I was started to provide a reference for conditions prior to the intrusion. Station 10 was revisited at the end of C-I (as St. 10b) and twice during C-II (as Sts. 10c and 10d) to estimate variability at one station.

Conductivity, temperature and pressure were measured with a SBE-11 CTD; a Sea-Tech transmissometer (25-cm path length) was used to measure light transmittance in the water. The CTD was lowered to within less than 10 m off the bottom. Water samples were collected using 12 5-L Niskin bottles mounted on a rosette sampler. Discrete samples were analyzed for oxygen (Winkler titration), chl *a* and pheopigment concentrations (Holm-Hansen et al., 1965). In addition, samples for chl *a* and pheopigment concentrations associated with particles larger than 70 μ m were also collected at discrete depths. Water was filtered through 70 μ m Nitex filters. The filters were analyzed for pigment concentrations and the filtrates were frozen in liquid nitrogen for flow cytometric analysis in the shore-based laboratory.

The hydrographic data (Figure 2) were plotted using an objective analysis mapping technique (Roemmich, 1983). The strength of this method is that it generates a contour map that provides the best fit to the data, given a user-determined error estimate and correlation function, and also generates an error map. These features are important when sparse, unequally spaced data are plotted, such as chl *a* concentrations from discrete water samples. For the continuous-profile CTD data, a correlation function was chosen to be Gaussian with a horizontal correlation e-folding length of one station and a vertical correlation e-folding length of 5 m. For the discrete samples, a variable vertical correlation was used that varied linearly from 10 m near the surface to 80 m at 250 m depth. The average value of properties within the intrusion were calculated using the interpolated fields derived from the objective analysis method, with the constraint that the relative error be less than 30%.



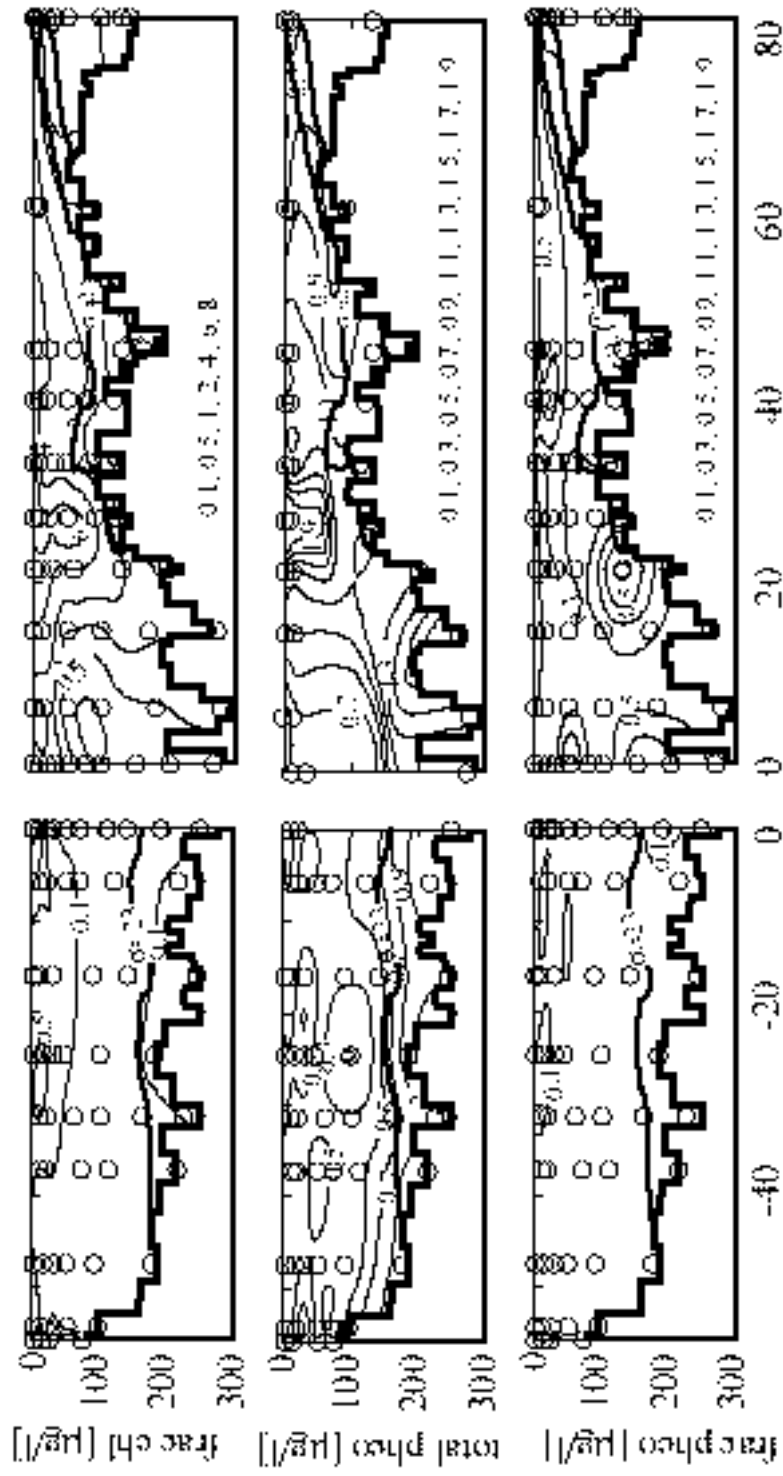


Figure 2. Density (σ_n), potential temperature (θ), oxygen (O_2), total chl *a* (chlorophyll *a*), frac chl *a* (chl *a* associated with particles $> 70 \mu m$), total pheopigment (pheo), and frac pheo (pheo associated with particles $> 70 \mu m$) during the two sections. Insets contain the contours used for each plot. Bold lines represent the isopycnal that defines the deep water intrusion ($\sigma_n=23.23.5$).

Flow cytometric analyses were performed on an EPICS Profile flow cytometer. In general the low concentration of particles observed (i.e., a few hundred particles per 200 ml) precluded statistical analysis of dynamics of changes in particle fluorescence characteristics (the error bars were larger than the changes in the signal). However, three different groups of particles were classified according to their fluorescence and scattering properties (Figure 3). The classification was computed using an objective method developed in our lab (Boss and Perry, unpublished); clusters of particle were differentiated by unique combinations of red and orange fluorescence and forward scatter.

Comparisons with laboratory cultures of two strains of *Synechococcus* sp. show that the F1 and F2 particle groups are similar in fluorescence and scattering patterns to *S. bacillaris* (clone SYNG) and *Synechococcus* WH7803 (clone SYNDC2), respectively a coastal and a pelagic cyanobacterium (Olson et al., 1988). Group F3 had fluorescence characteristics similar to F2 but with much greater forward scatter, presumably due to larger size. The identity of the F3 group is unknown, but these particles could potentially be fragments of fecal material, egested cells or autotrophic dinoflagellates.

To assess the degree to which dilution controlled the changes in particle concentration, 20-L water samples were taken from 10 m at both St. 10b and St. 1 and from the bottom at St. 9. The water samples were stored at 8° C room in the dark and were subsampled during the week between the cruises to provide a reference for changes observed in the intrusion waters during section C-II.

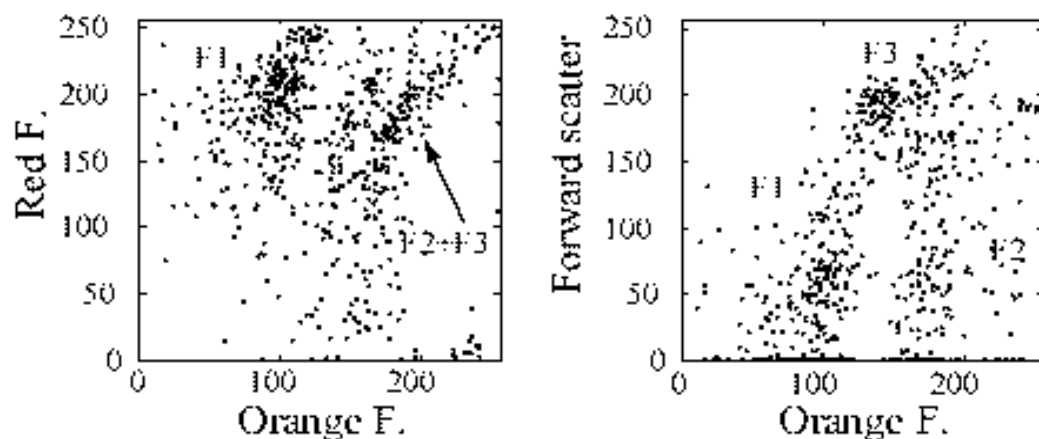


Figure 3. Flow cytometric analysis of bottom water from St. 16. Three classes of particles are distinguished based on chlorophyll *a* fluorescence (Red F.) and forward scatter (an indication of particle size). The F1 particles are uniquely distinguished by their lower orange fluorescence, while the F2 and F3 particles are distinguished based on differences in forward scatter. The distribution of each group within the water column is shown in Figure 6.

Observations

Hydrography

During the C-I section a strong front was observed between Sts. 5 and 6 (right panels, Figure 2). This front was associated with the intense downwelling that resulted from the interaction of flow and inlet topography. A similar feature was observed at the same location in the high-resolution measurements made by Turner and Gregg (1995). Two intrusive water masses were characterized during the C-I section: one to the north and one to the south of the front. The water mass to the south ($\sigma_\theta \sim 22.75$) had θ -S properties (Figure 4) and high oxygen and pigment concentrations indicative of a mixture of surface Puget Sound waters and oceanic waters. The temperature, pigment, and particularly the oxygen contours in Figure 2 all indicate that this water mass was intruding, at depth, into the main basin. We refer to this water mass as the first intrusion.

To the north of the front, a tongue of dense ($23.2 > \sigma_\theta > 22.9$) water could be observed at the bottom at St. 7 and could be traced (with sloping isopycnals) to the surface in the Straits (St. 1). This water mass had similar properties to those observed in the bottom of the main basin during the second cruise; hence, we refer to this dense water as the source of the deep-water intrusion.

Water properties in the bottom of Puget Sound at St. 10 (Figure 5) indicate that by the end of the first section (10b) a warmer water mass had penetrated below 180m. A closer look reveals the existence of two maximums in temperature (one at 180 m and a second at the bottom). These data are suggestive of two separate intrusive features that can also be observed in the θ -S properties at St. 9 (Figure 4). Each intrusive water mass was formed by a different mixture of oceanic and Puget Sound water, with the density determined by the proportion of each in the admixture.

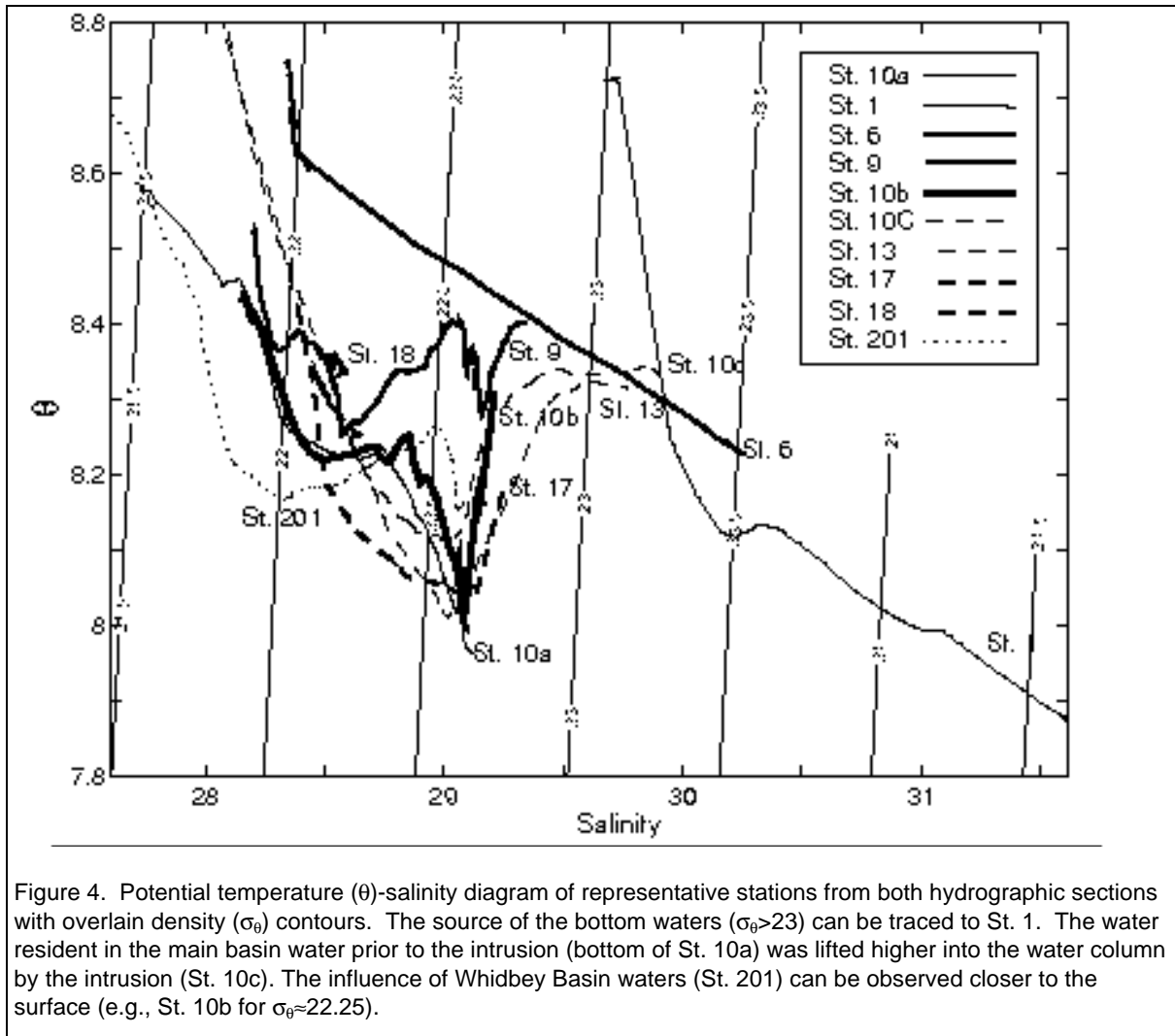


Figure 4. Potential temperature (θ)-salinity diagram of representative stations from both hydrographic sections with overlain density (σ_θ) contours. The source of the bottom waters ($\sigma_\theta > 23$) can be traced to St. 1. The water resident in the main basin water prior to the intrusion (bottom of St. 10a) was lifted higher into the water column by the intrusion (St. 10c). The influence of Whidbey Basin waters (St. 201) can be observed closer to the surface (e.g., St. 10b for $\sigma_\theta \approx 22.25$).

Data from the C-II section, taken one week later, are shown in the left panels of Figure 2. The water below ~ 170 m had the same θ -S properties as the dense deep-water intrusion in the C-I section. The volume of water below 170 m in the main basin of Puget Sound was approximately 7 km^3 (based on the 300 m resolution, bathymetric data base compiled by Dr. Miles Logsdon, University of Washington). We used a simple mass balance to calculate the horizontal length of the intrusion, based on an estimated width for Admiralty Inlet of ~ 7 km and a vertical scale for the deep-water intrusion of ~ 50 m (Figure 2).

We estimated that the length of the intruding water mass should be approximately 20 km. Because the distance between Sts. 1 and 7 is about 30 km, we believe that our first hydrographic section captured the bulk of the waters that penetrated below 170 m into Puget Sound. The conservation of θ -S properties in the intrusion indicates that this dense water penetrated with little mixing. These results are consistent with the notion that during neap tides mixing and modification of intruding oceanic waters are minimal.

The θ -S properties at depth at St. 201 in Whidbey Basin show a similar intrusive tongue as that observed at St. 9 during C-I (yet somewhat mixed with Puget Sound intermediate water, Figure 4) implying that the first intrusion penetrated into the Whidbey basin. The θ -S properties at the entrance of the Tacoma Narrows (St. 18) indicate that water there was upwelled from intermediate depths in the main basin (~100 m, Figure 2). Note that the water that resided at depth prior to the intrusion (bottom of St. 10a) was at about 70 m during C-II (Figures 4–5), uplifted by the deep intrusion and subsequent intermediate ones.

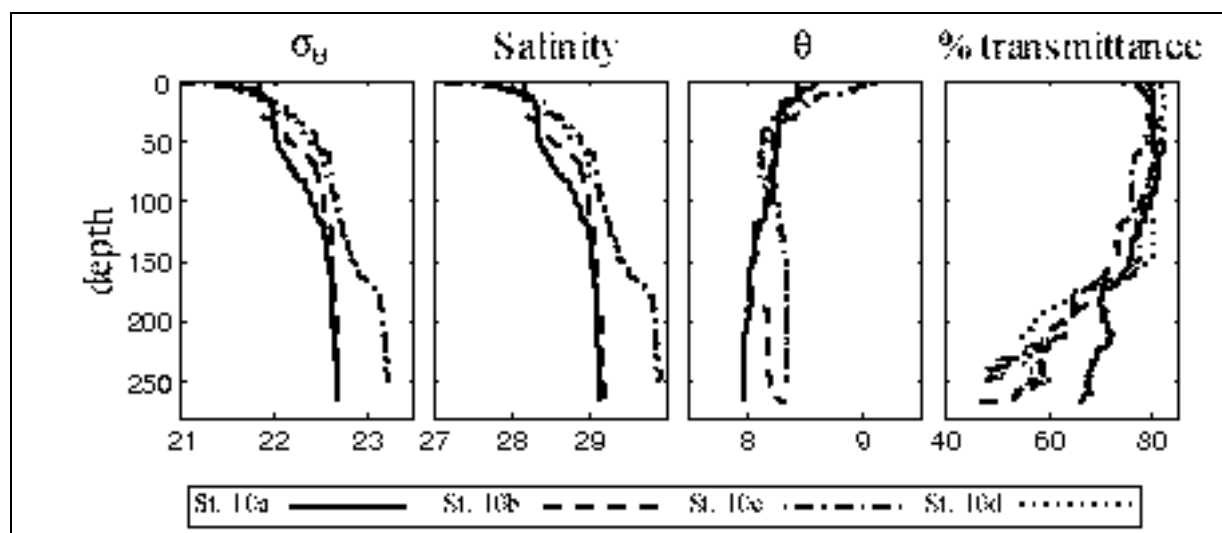


Figure 5. Density (σ_θ), salinity, potential temperature (θ), percent (%) light transmittance at St. 10 before (St. 10a) and after bottom intrusions entered Puget Sound (St. 10 b, c, and d).

Table 1. Average water properties within the deep-water intrusion ($23.2 > \sigma_\theta > 22.9$), and standard deviations, based on interpolation by objective analysis (see Figure 2 for symbols and units). St. 10a water properties at 202 m, measured prior to the intrusion, are given for reference.

	σ_θ	θ	O ₂	Chl <i>a</i>	Chl <i>a</i> >70 μ	Pheo	Pheo >70 μ
Section-I	23 (0.1)	8.45 (0.01)	8.6 (0.3)	2.3 (0.4)	0.9 (0.2)	0.9 (0.3)	0.16 (0.1)
Section-II	23 (0.1)	8.32 (0.01)	8 (0.1)	0.4 (0.1)	0.1 (0.05)	0.9 (0.4)	0.02 (0.02)
10a (202 m)	22.6	8	7.98	0.24 (.02)	0.03	0.42 (.05)	0.07

Biologically Active Tracers

A phytoplankton bloom ([chl *a*] > 8 mg/m³) occurred at Sts. 5 and 6 during the C-I section. Downwelling of water with high chl *a* concentration was observed to 100m depth with subsequent entrainment into intermediate waters (Figure 2). About 80% of the chl *a* concentration in the downwelling water was associated with the fraction of cells larger than 70 μ m; these data suggest that the

bloom was due to large cells or chain-forming diatoms (diatom chains were found in water a sample collected from the surface at St. 1, S. Menden-Deuer, personal communication). In the water comprising the deep-water intrusion only 40% of the chl *a* was associated with cells larger than 70 m (Table 1), indicating that the waters in the Straits of Juan de Fuca contained relatively more small cells than the surface waters of Puget Sound. In contrast a higher proportion of pheopigments, degradation products of chl *a* formed during zooplankton grazing of phytoplankton, were found in the size fraction smaller than 70 m. These findings could be indicative of high grazing rates by small zooplankton. Small dinoflagellates (*Protoperidinium* sp.) that feed on large diatom chains were observed in a water sample collected from the surface waters at St. 1 (S. Menden-Deuer, personal communication). Another possibility is that pellets of larger zooplankton (~300 m copepods, B. Frost, personal communication) break within the water column or during filtration. Buck and Newton (1995) found in Dabob Bay, Washington, that dinoflagellates were an important source of small fecal pellets. These pellets were devoid of pigments, although Strom (1993) has shown that the fecal pellets of certain dinoflagellates do contain pheopigments. Why pheopigments were more abundant in small particles, relative to chl *a*, in our samples remains an open question.

At St. 10 prior to the intrusion, concentrations of chl *a* and pheopigments near the bottom were 0.24 and 0.4 mg/m³ respectively, much lower than concentrations within the deep intrusion (2.4 and 0.9 mg/m³ respectively, Table 1). A week later, chl *a* concentrations within the deep-water intrusion dropped by more than 80% while pheopigments at depth had similar values to those in the intrusion tongue (~0.9 mg/m³). The loss of chl *a* could be due both to sinking of the large cells to the bottom and to conversion of chl *a* to pheopigments through zooplankton grazing with subsequent sinking of pellets. In both hydrographic sections the bulk of the measured pheopigments were from the fraction of particles smaller than 70m. Small particles sink faster than large particles, and thus are expected to stay longer in the water column.

Oxygen concentrations within the intrusion were reduced from 8.6 to 8.0 ml/L during the week following the intrusion (Table 1). Assuming a stoichiometric ratio of 1.0 mol O₂ respired per 1.45 mol C oxidized and a gram ratio of C/chl *a* of 30, oxidation of the carbon associated with 2 mg/m³ of chl *a* would result in the consumption of 0.2ml/L, about 30% of the observed reduction.

Another potential source of organic carbon is Seattle's sewage outfall, which can release up to 400 million gallons of sewage a day, with a maximum concentration of dissolved organic carbon of 30 mg/L. Assuming an extreme scenario, i.e., all the organic carbon gets oxidized within the deep water mass (i.e., an input of 1 part sewage for ~650 parts of deep water), the disappearance of only another 0.15 ml/L can be explained. In order to achieve an oxygen mass balance, we have to assume either that organic material is respired within the sediment (i.e., the sediments are a sink for the water column's oxygen) or that organic matter previously deposited on the bottom is resuspended by the intrusion and respired within the water column (indeed, low transmittance is observed near the bottom). It is interesting to note that intrusions can both import relatively oxygenated surface waters as well as the biogenic material whose degradation will consume oxygen. The contribution of surface carbon to deep waters in Puget Sound by sinking is a relatively unimportant route for carbon transport relative to advective transport by intrusion (Winter et al., 1975).

Flow cytometric analysis of the particles smaller than 70 m revealed a single group that had significantly higher concentrations near the surface (F1, similar to the coastal cyanobacteria, SYNG, Figure 3). This group also had a secondary concentration maximum associated with the intrusive waters at the bottom of the main basin during the second cruise. The distribution of the F1 particles near the Tacoma Narrows (Sts. 17 and 18) tracked the upwelling of intermediate waters into the Narrows and the mixing with waters with low concentrations of F1 particles. These data display clearly the effect of mixing at the Narrows in homogenizing water properties.

Compared with the deep-water intrusion waters during C-I, concentration of F1 particles dropped from ~600 cells/200 ml to ~300 cells/200 ml in the bottom of the main basin during C-II, due possibly to dilution, grazing and mortality. Prior to the intrusion there were 90 cells of F1 at depth. Group F2 had a small vertical gradient in comparison to F1. Its values increase ~200 near the surface and are fairly high at depth (~130). Prior

to the intrusion there were 70 cells/200 ml for this group at the bottom of St. 10a. In laboratory incubations of collected samples, the concentration of particles associated with phytoplankton (F1+ F2) were found to decrease by 40–60% after a week (data not shown). Assuming that the trophic dynamics within the incubation bottles were similar to those within the deep water, these observations suggest that little dilution occurred in the intrusive water body, as observed in the hydrography. Notice that the small cyanos are better preserved than the bulk total and fractionated chl *a* that are reduced by more than 80%.

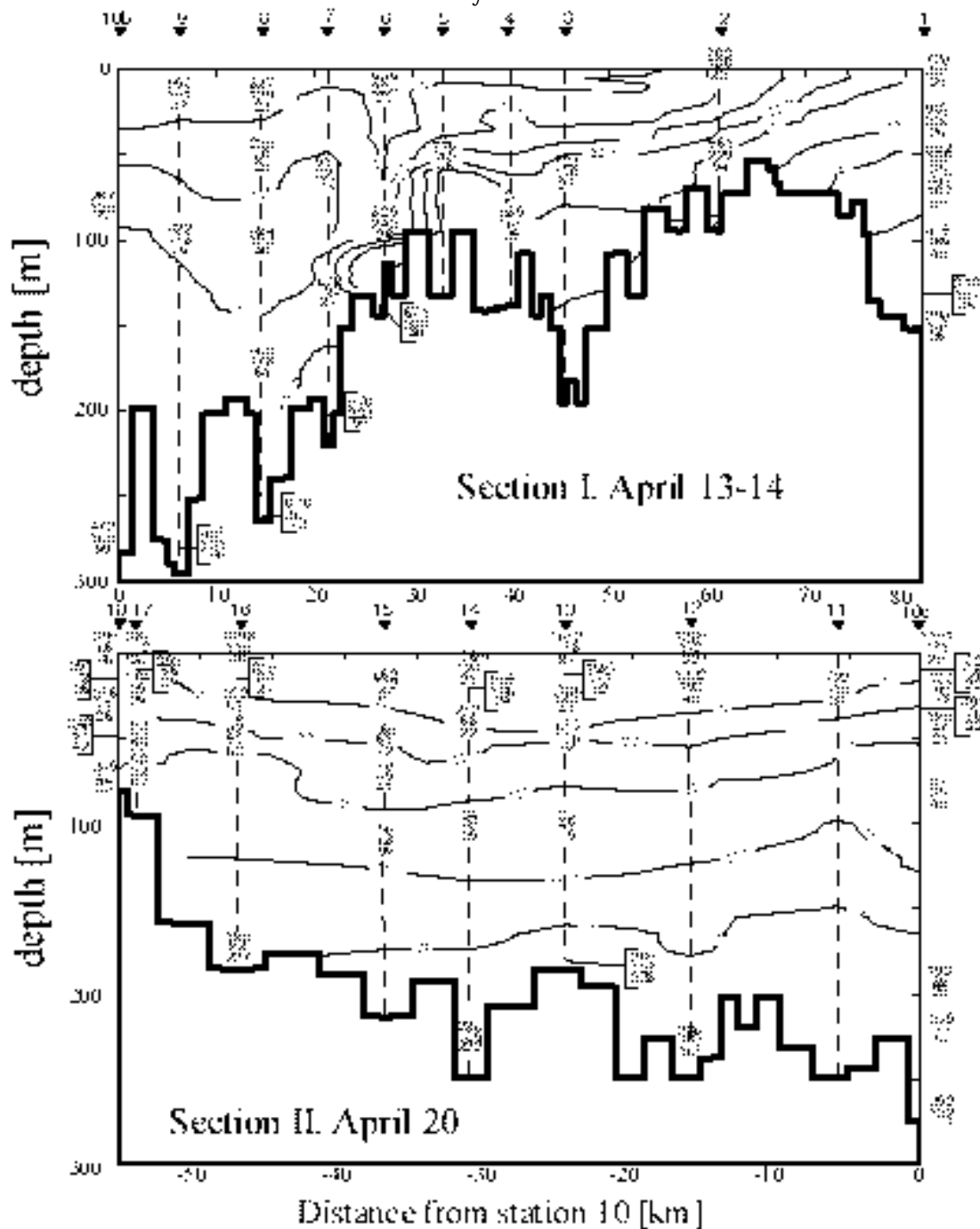


Figure 6. Distribution of three groups of particles classified from flow cytometric (see Figure 3). Concentrations of each type of particle (cell number per 200 μ l) are given in a cluster of three numbers for F1 (top), F2 (middle), and F3 (lower) particle groups. Solid lines are density contours (σ_θ).

Group F3 increased near the bottom of Puget Sound, was low near the surface and did not have an apparent source except for being correlated with low optical transmittance (Figure 4, values prior to the intrusion are 70 particles/200 ml). These data suggest that the bottom may be the source of these particles and are consistent with the idea that organic material was resuspended from the bottom sediments. This may be the case if the particles are broken fecal material. Few F3 have been observed in samples from the incubation bottles, except for samples collected at the bottom of St. 9, where their numbers hardly change during the incubation.

Conclusions

An intense intrusion of deep water into the main basin of Puget Sound was recorded. The intrusion is saltier (0.8 psu), warmer (0.4° C), and denser (0.6 g/L) than the water residing in the main basin prior to the intrusion (Figure 4). Compared to past studies of intrusions (Cannon and Laird, 1978; Geyer and Cannon, 1982; Cannon et al., 1990) that were mostly observed using mooring data, this intrusion is one of the strongest observed. For average intrusions, changes in salinity are ~0.2 psu (Geyer and Cannon, 1982). While it was suggested (Lavelle et al., 1991) that the summer season should be the season of strongest intrusions, our measurements together with past studies (op. cit.) have shown the spring is a season of very strong intrusions. Reasons for the greater strength of spring intrusions are the maximum diurnal inequality and relative weakness of the neap tides close to the equinox (Holbrook, personal communication) and the weakening of southerly winds that prevail during winter.

Fractionation of pigments data and the data derived using flow cytometry suggest that small cells are better preserved within the intrusion than large cells. The link between the size of particles containing pheopigments and the size of phytoplankton cell and their predators needs further study before it can be used as an indicator of trophic dynamics.

Two classes of small particles, with optical characteristics similar to cyanobacteria, were quantified. The particle with optical properties that resembled coastal cyanobacterial species dominated during our cruises. A third, unidentified group of particles, which does not behave in a similar manner to the phytoplankton, was found in significant concentrations near the bottom of Puget Sound. The most abundant group (F1) was shown to be a useful tracer for downwelling waters. Under dark conditions, it had a half-life time of about six days, a period long enough to be observed through the intrusion penetration and short enough to decrease prior to the entry of a new intrusion.

Winter et al. (1975) have studied the dynamics of pigments during spring and summer in Puget Sound. They found large concentration of pigments (they did not separate chl *a* and pheopigments) to occur at a fortnightly periodicity, in association with increased salinity in the bottom. They have hypothesized that bottom water renewal processes are the underlying mechanism, a hypothesis we were able to confirm. More than 80% of the chl *a* concentration disappeared from the bottom waters within a week time, an indication of the rapid consumption and/or sinking of the pigments in the deep-water intrusion. The impact on oxygen was rapid with a reduction of ~0.6ml/L in one week. Whether the reduction is solely due to the intrusion still needs to be determined.

The predictability of major circulation feature in Puget Sound, as highlighted here for a deep-water intrusion, could be used to maximize the rate of transport of anthropogenic contaminants away from Puget Sound into the Strait of Juan de Fuca. On average, 52% of the water entering Admiralty Inlet from Puget Sound recirculates into other Puget Sound layers (Cokelet et al., 1991). But timing the release of contaminants and adjusting their density, so that the smallest amount gets refluxed into the Sound at the sill, should lower the refluxing ratio of contaminants significantly. Use of numerical models that assimilate hydrographic and wind data at key locations in Puget Sound would increase greatly the ability to accurately predict the circulation in Puget Sound.

Acknowledgment

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